ENERGY DISSIPATION CHARACTERISTICS OF 3-D FRAMED STRUCTURES NEAR DYNAMIC INSTABILITY THRESHOLD

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SUMMARY

One of the outcoming issues related to the ultimate resistance limit state of structures subjected to strong ground motions is the effect of gravity forces in the overall stability of the structural dynamic response (dynamic instability). This study analyzes the near-collapse energy dissipation characteristics of a five story framed structure when subjected to two intrinsically different bidirectional ground motions applied at different angles of incidence. A reference model is designed first and, from this basic design, a set of models are defined by increasing the resistance of certain elements of the reference model in order to induce specific unique mechanism patterns throughout the response. Then, all systems are subjected to the action of the ground motion records acting at different angles of incidence, and the minimum required values of the seismic base shear coefficient to prevent structural dynamic instability (dynamic collapse coefficient, C_C) and the associated collapse mechanism patterns are obtained. Results indicate that C_C and the associated collapse mechanism pattern vary with the angle of incidence, except for purely rotational mechanisms. They also indicate that C_C can be predicted from the study of a set of predetermined mechanism patterns, which could be represented by simpler systems, like equivalent single degree of freedom systems. Finally, the effect of the angle of incidence, collapse mechanism and characteristics of the ground motion on the energy dissipation characteristics of three different induced mechanism models (translational, rotational, and combined) are illustrated and discussed.

INTRODUCTION

The destabilizing effect of gravity loads on buildings subjected to severe ground motions can lead to catastrophic collapse (i.e., dynamic instability) when the structure is forced to develop significant inelastic excursions during the response. Although prevention of collapse is a fundamental objective of seismic design, there is significant uncertainty on the suitability of current procedures to provide adequate margin of safety against dynamic instability [NEHRP, 1991]. Studies on dynamic instability in multistory framed structures have pointed out the critical role that the failure mechanism plays in the safety of structures against collapse [Nakajima et al 1990, Bernal 1990, Bernal, 1992]. They also report that standard seismic designs may not lead to adequate safety against instability, depending on the available overstrength and the type of controlling failure mechanism.

Three dimensional geometry of most real buildings introduces the possibility of the development of rotational failure mechanisms [Sordo and Bernal, 1992, 1994 and 1996], and the effect of ground motion bidirectionality and its angle of incidence on the structure adds substantial complexity to the problem. Although potential for failure due to torsional instability has long been recognized, there are relatively few studies that directly address this issue. Most of these studies focus on dynamic instability of single story systems, like the pioneering work of Shibata et al (1969) or more recent studies [Morino and Uchida, 1980, Sordo and Bernal, 1992 and De Stefano and Rutenberg, 1999]. Their results indicate that it is significant the influence of rotational inelastic response in reducing the stability threshold of such systems. They also highlight the importance on the simultaneous

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consideration of the ground motion components for the adequate assessment of dynamic instability. However, single story systems do not adequately represent the complexity of the tridimensional, multistory mechanism patterns, so the inherent limitations of such systems must be kept in mind when projecting the significance of the results to realistic three dimensional structures.

Studies on dynamic instability in three-dimensional multistory structures are extremely scarce. An exploratory study on dynamic instability of a unidirectional multistory structure reported by Sordo and Bernal (1992) concluded that the three dimensional shape of the failure mechanism is likely to play a fundamental role in the safety against instability of multistory structures. Sordo and Bernal [1993] later examined the dynamic instability phenomenon on a five-story building subjected to the effect of different unidirectional and bidirectional ground motions. Here, the authors discussed the importance of considering the complete multidirectional ground motion in the analyses, particularly when rotational failures are prone to be developed.

Certainly, the development of rational simplified methodology for the analytical prediction of dynamic instability in three dimensional structures is a fundamental need for the practical structural safety assessment of real buildings. One of the most challenging issues concerning estimates or prediction of a multistory structural system is the feasibility of representing the complex behavior of such systems in a simple and rational manner. Although some efforts have been done so far in achieving an adequate equivalent SDOF approach to planar structural systems [Bernal 1992, 1998], scarce studies [Sordo and Bernal, 1994] have been made so far to implement this concept in a more generic treatment of dynamic instability of three dimensional multistory systems. An attractive approach to attain this goal consists in defining a SDOF system that has energy dissipation properties equivalent to those of the three dimensional structure. Energy based concepts were first introduced by Housner [1956], and have recently been extensively studied as a promising alternative to the traditional strength-ductility design procedures [Uang and Bertero 1988, Bertero et al 1996, among others]. The main advantage of utilizing energy concepts in the study of three dimensional dynamic instability bears on the reduction of the problem to the evaluation of two scalars, i.e. the energy capacity and the energy demand.

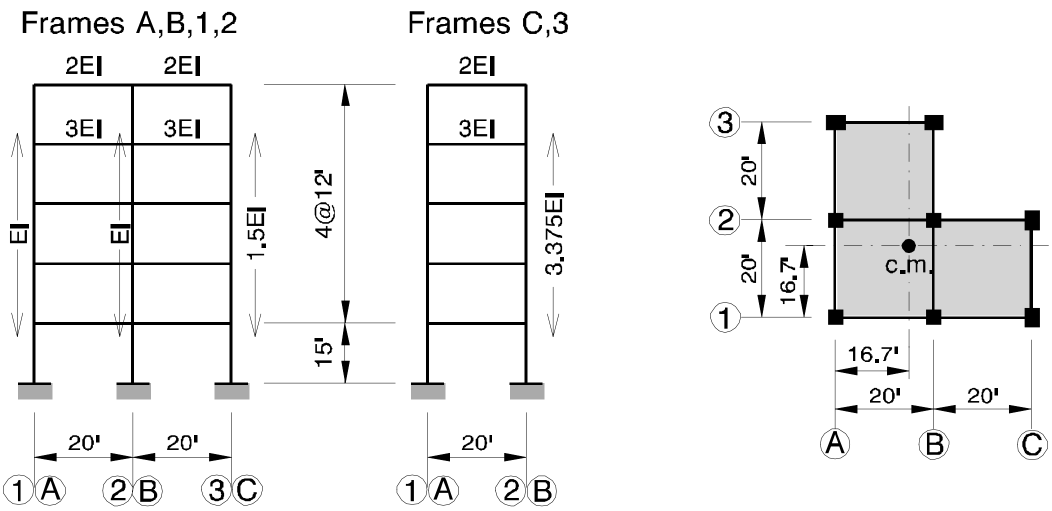
This paper contributes to the assessment of dynamic instability in three dimensional multistory structures by analyzing the effects of two bi-directional ground motions with different duration, frequency content and directionality characteristics on a five story three-dimensional structural model having different orientations relative to the ground motions. The minimum base design coefficient needed to prevent dynamic instability (*dynamic collapse coefficient*), and the mechanism patterns leading to impending collapse are obtained for the different orientations in the first part of the paper. Additionally, localized element strengths are modified to induce predefined mechanism patterns throughout the response, and the effects of the shape of these induced mechanisms on the dynamic collapse coefficient for the different orientations are discussed. On the second part of the paper, kinetic, damping, hysteretic and external energy dissipation values associated to the near collapse response are obtained and compared to the dissipation energy values corresponding to the elastic model for the different structural orientations with respect to the ground motion.

METHODOLOGY

In order to study the dynamic instability phenomenon and the near-collapse energy dissipation characteristics of three dimensional framed structures when subjected to bidirectional ground motions, an L-shaped, five story framed structure is designed for the 1991 NEHRP recommended provisions (NEHRP, 1991) as a reference model. From this basic design, a set of induced mechanism models are defined by increasing the resistance of certain elements in order to induce specific mechanism patterns throughout the response. Then, all the systems are subjected to the action of two bidirectional ground motion records with different characteristics; El Centro, California, 1941 (CEN) and Secretaria de Comunicaciones y Transportes, Mexico City, 1985 (SCT), which differs to the CEN record in its much stronger directionality, longer duration, and harmonic (narrow-banded) characteristics. These records are applied at a range of different angles of incidence (from 0 to 180^o, which represents all possible orientations due to the particular characteristics of the structure). For each angle of incidence, the design base shear coefficient is scaled down, from a starting value associated to elastic behavior, until impending collapse is attained. The base shear coefficient associated to this point is called in this paper the dynamic collapse coefficient (C_C), and it is defined as the minimum required value of the seismic base shear coefficient to prevent structural dynamic instability. The influence of the angle of incidence and the mechanism patterns on this value and on the kinetic, damping, hysteretic and external energy dissipation characteristics associated to the near collapse response of the models are then evaluated.

Reference model description.

The building selected for this exploratory study is a 5 story structure with an L shaped plan, with identical characteristics in two perpendicular directions of analysis, as depicted in figure 1. The resisting moments of the structural elements correspond to the internal moments obtained from a static analysis using the seismic load conditions provided by the 1991 NEHRP Recommended Provisions. The beams are designed only for the seismic loads, and not for the dead and live loading conditions. The distributed characteristics of the beam loads are then ignored in the nonlinear dynamic analysis, to keep consistency with the design. This approach aims to minimize the effect of overdesign in some elements, in order to have a structure where several mechanisms can be formed during the dynamic response. Notice that, in a standard design, one predominant dynamic mechanism is expected to appear due to the overstrength that some of the elements will have. Also, for simplicity, the elements are considered to be perfectly elastic-plastic moment resisting elements with no biaxial interaction effect. Viscous damping of 5% of the critical is considered for the first three modes of vibration in the analysis.



	MODE 1	MODE 2	MODE 3
T_i (s)	1.00	0.956	0.622
θ_i	.0249	.0212	.00959
Γ_i	1.63	1.67	0.368

EI=2712Kips-ft^2 **m_i**=7.51Kips-s^2/ft **r_i**=15.6ft **τ**=1.2

Notation: **T_i** and **Γ_i** are the modal period and participation factor; **E** is Modulus of Elasticity; **I** is Inertia; **m_i** and **r_i** are the mass and radious of gyration per floor (same for all floors); and **τ** is the total vertical load for P-Δ effects as a ratio to the total weight considered for seismic analysis and design.

θ_i is the elastic modal stability coefficient, and can be computed as $1.0 - (T_i / T_i^*)^2$, where T_i^* and T_i are the modal elastic periods with and without considering P-Δ effects, respectively.

Figure 1. General characteristics of the reference model considered in this study.

Induced mechanism models description.

From the basic design for the structural model, previously noted as *reference model*, a series of systems were generated by increasing the resistance of localized elements in order to ensure the development of different specific mechanisms. These models are called in the body of this paper *induced mechanism models*, and are analyzed to study the influence of the particular plastic mechanism pattern in the energy dissipation characteristics at impending collapse. The selection of the specific induced mechanisms (shown in table 1) was based on the criteria recommended by Sordo and Bernal (1994). This consists on selecting those mechanisms with the least maximum monotonic energy dissipation capacity (defined in table 1) that also satisfy minimizing the base shear associated to a predefined horizontal load pattern applied through the height. Three additional induced mechanisms (C3-02, B2-01 and B2-02 in table 1) associated to relatively high energy dissipation capacities were also considered, for comparison purposes. All these mechanisms and their maximum monotonic energy dissipation capacities are described in table 1.

Table 1. Induced mechanism models for this study, and associated monotonic energy dissipation capacities.

Induced mechanism	Monotonic energy dissipation capacity
C3-01 (mech from base to level 1 and pivoting over intersection of axes C and 3)	620 kips-in
TX-01, TY-01 = mech from base to level 1 and translational in X, Y direction	626 kips-in
TX-02, TY-02 = mech from base to level 2 and translational in X, Y direction	906 kips-in
C3-02 = mech from base to level 2 and pivoting over intersection of axes C and 3	1148 kips-in
B2-01 = mech from base to level 1 and pivoting over intersection of axes B and 2	1573 kips-in
B2-02 = mech from base to level 2 and pivoting over intersection of axes B and B	2028 kips-in

Monotonic energy dissipation capacity is defined as the energy needed to statically drive the structure to the fully developed mechanism displacement configuration where the internal forces are in equilibrium with the vertical loads through a 2nd order analysis, and it does not depend on the particular load pattern utilized.

RESULTS

For each angle of incidence and structural model, design base shear coefficient is varied from a high starting value until associated response is such that impending collapse is detected. The design base shear coefficient associated to this point is called the *dynamic collapse coefficient* (***C_C***), and the plastic mechanism at impending collapse is named *collapse mechanism*, which is adequately detected after examining the interstory drift increments in time. This collapse mechanism is predefined for the induced mechanism models, but it is arbitrary for the reference model. The C_C values for different angles of incidence are indicated in figure 2. Here, it can be seen that variation of C_C with the angle of incidence is most notorious in translational induced mechanisms (TX-01, TX-02, TY-01 and TY-02) and for the most directional ground motion (SCT). The purely rotational mechanism (B2-01) shows no significant influence from the angle of incidence for either ground motion. Orientation does not affect significantly the C_C values for the reference model, due to the similar energy capacity characteristics (table 1) of the different mechanisms that develop.

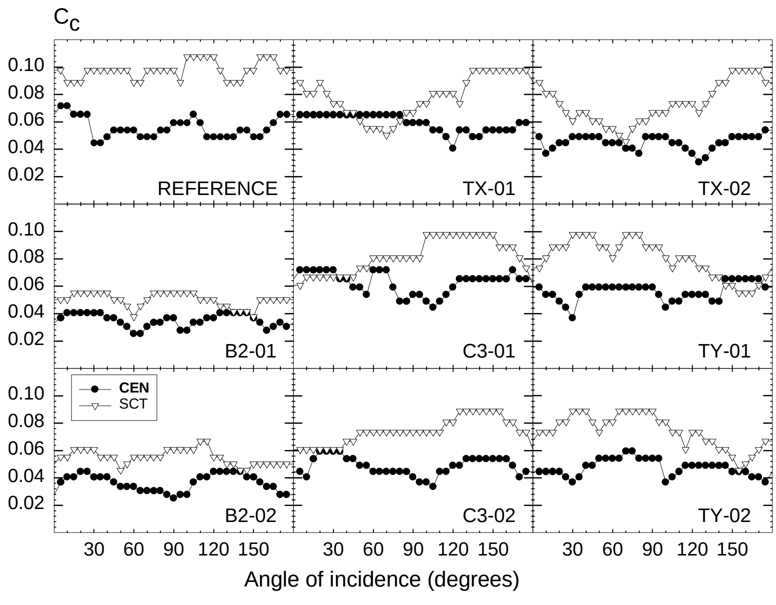


Figure 2. Dynamic collapse coefficients (C_C) for the reference and induced mechanism models.

The C_C values for the reference model are also indicated in table 2, together with their corresponding collapse mechanisms. This table shows that the most critical mechanisms are C3-01 and TX-02, as they are associated to the largest C_C values (highlighted in table 2). Also, it is seen that the rotational mechanisms are more likely to develop under the action of CEN ground motion as compared to the results for the more directional record SCT. It is worth noting that the observed collapse mechanisms of the *reference model* are associated to the minimum values of the maximum monotonic energy dissipation capacity shown in table 1.

Table 2. Dynamic collapse coefficients and associated collapse mechanism patterns for the reference model.

CEN						SCT					
Angle	C_C	Mech	Angle	C_C	Mech	Angle	C_C	Mech	Angle	C_C	Mech
0°	0.065	C3-01	90°	0.059	TX-02	0°	0.098	TX-02	90°	0.098	TY-02
10°	**0.072**	**C3-01**	100°	0.059	TX-02	10°	0.089	TX-02	100°	**0.108**	**C3-01**
20°	0.065	C3-01	110°	0.059	TX-02	20°	0.089	TY-02	110°	**0.108**	**C3-01**
30°	0.045	TX-01	120°	0.049	TY-01	30°	0.098	TY-02	120°	**0.108**	**C3-01**
40°	0.049	C3-01	130°	0.049	TY-01	40°	0.098	TY-02	130°	0.089	C3-01
50°	0.054	C3-01	140°	0.054	TX-02	50°	0.098	TY-02	140°	0.089	TX-02
60°	0.054	TY-01	150°	0.049	TX-01	60°	0.089	TY-02	150°	0.098	TX-02
70°	0.049	TY-01	160°	0.054	TX-01	70°	0.098	TY-02	160°	**0.108**	**TX-02**
80°	0.054	TY-02	170°	0.065	C3-01	80°	0.098	TY-02	170°	0.098	TX-02

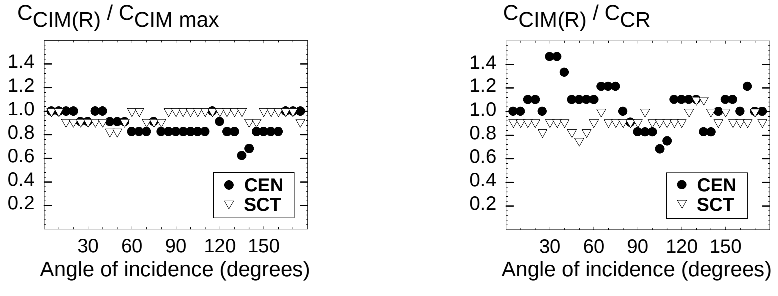
C3-01 = mechanism from level 0 (base) to level 1 and pivoting over intersection of axes C and 3
TX-01=mech. from lev. 0 to lev. 1, X-translational TX-02= mech. from lev. 0 to lev. 2, X-translational
TY-01=mech. from lev. 0 to lev. 1, Y-translational TY-02= mech. from lev. 0 to lev. 2, Y-translational

Prediction capability of induced mechanism models.

In the study of dynamic instability of three-dimensional multistory buildings, it is relevant to explore simplifying procedures that might predict the values of C_C that ensure structural stability. The major difficulty for such procedures is to accurately predict the specific mechanism pattern that would lead the structure to dynamic collapse during the response. A first step is done in this direction, by comparing the values of C_C for the different induced mechanism models with those associated to the reference model. This comparison aims to assess the potential to detect the mechanism that leads to dynamic instability from the study of a set of predetermined mechanism patterns. These induced mechanism models could then be simplified to a set of corresponding simpler systems, like single degree of freedom systems.

Figure 3a shows the C_C values associated to the induced mechanism models with identical mechanism pattern as that observed from the reference model ($C_{CIM(R)}$), normalized to the maximum C_C for any induced mechanism model at the same angle of incidence ($C_{CIM\ max}$). It is noticed that this ratio is, in general terms, close to unity, so the maximum C_C value for all induced mechanism models seems to adequately predict the C_C value associated to the induced mechanism model that represents the mechanism detected in the reference model.

Figure 3b shows the value of $C_{CIM(R)}$ normalized to the value of C_C corresponding to the reference model (C_{CR}) at the same angle of incidence. Here it can be seen that, specially for the angles of incidence associated to the critical C_C values (around 10° for CEN and 110° for SCT, as highlighted in table 1), the reference model C_C can adequately be predicted from the corresponding induced mechanism model. From these results, it seems reasonable to predict the C_C value of the reference model by obtaining the maximum C_C from all induced mechanism models, which are more likely to be represented by simplified systems than the reference model.



(a) (b)

Figure 3. (a) C_C for the induced mechanism model corresponding to the observed mechanism from the reference model ($C_{CIM(R)}$), normalized to the maximum C_C for any induced mechanism at that angle of incidence ($C_{CIM\ max}$) **(b)** C_C for the induced mechanism model corresponding to the observed mechanism from the reference model ($C_{CIM(R)}$), normalized to the C_C corresponding to the reference model (C_{CR}) at the same angle of incidence.

Energy dissipation characteristics near dynamic instability condition.

The maximum relative kinetic, damping, hysteretic (including P-Δ effects) and total energy values at near-collapse response for induced mechanism models B2-01, C3-01 and TY-01 are graphed in figures 4 and 5 for CEN and SCT ground motion records, respectively. These specific mechanisms are representative of three main types of plan mechanism patterns, that is, purely rotational (B2-01), mixed rotational and translational (C3-01) and purely translational (TY-01). The maximum energies obtained from a model designed to remain elastic throughout the response are also included in these graphs. For this particular structure, the energy demanded from the elastic model does not significantly vary with the angle of incidence when subjected to CEN or SCT, due to the similar dynamic characteristics of the first three modes of vibration (Figure 1). This situation was purposely chosen to enhance the effect of different mechanism patterns in energy dissipation as a function of the angle of incidence. Different observations from figures 4 and 5 are discussed in the following paragraphs.

Kinetic and damping energies for the elastic system appear to be upper bound values of the corresponding energies associated to near-collapse response for CEN but lower bound values when the models are subjected to SCT. However, hysteretic energies for the elastic system are lower bound values of the corresponding energies associated to near-collapse response for both ground motion records.

The amount of external (total) relative energy does not significantly depend on the angle of incidence or the mechanism pattern for the CEN ground motion. However, the opposite tendency is seen when the models are subjected to the SCT ground motion. This is a consequence of the strong directionality of the SCT record.

The amount of external energy demanded from the models is similar to the one demanded from the elastic model for the CEN ground motion. However, when they are subjected to SCT, the external energy demand becomes much higher, as SCT is a very long and cyclic ground motion, so maximum energy dissipation is mostly due to plastic response. This also explains the large hysteretic vs total energy ratios for SCT as compared to CEN.

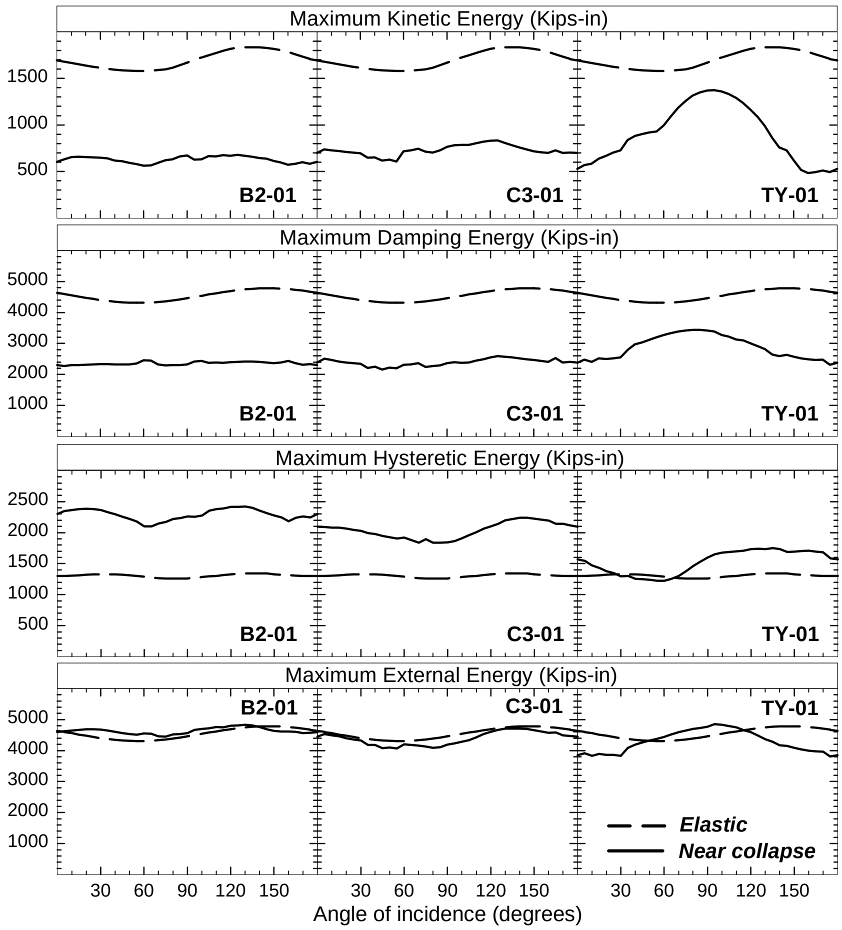


Figure 4. Energy parameters for B2-01, C3-01 and TY-01 models subjected to CEN ground motion.

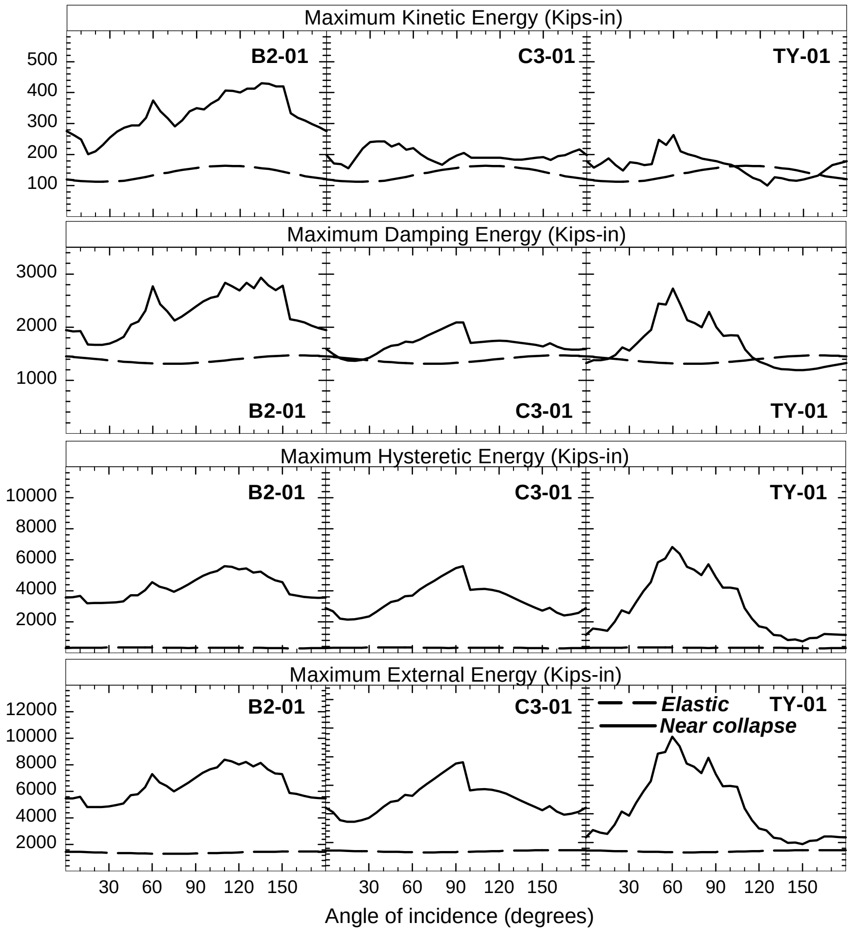


Figure 5. Energy parameters for B2-01, C3-01 and TY-01 models subjected to SCT ground motion.

An interesting additional observation is that, for SCT record, the external energy associated to translational model TY-01 is similar to the elastic model energy around an angle of incidence of 150^o. This is the angle of incidence where the strongest ground motion component is perpendicular to the induced translational mechanism direction. In this case, most of the overall energy (associated to the strong component) is dissipated elastically. Notice that, for a 60^o angle of incidence (strong component in the direction of the translational mechanism), the elastic energy demanded from the weakest component becomes then negligible, and the energy demanded by the strong component activates plastic energy (cumulative) dissipation

SUMMARY AND CONCLUSIONS

In order to explore the near-collapse energy dissipation characteristics of three dimensional framed structures when subjected to bidirectional ground motions, an L-shaped, five story framed structure was designed for 1988 NEHRP recommended provisions as a *reference model*. From this basic design, a set of systems (*induced mechanism models*) were defined by increasing the resistance of certain elements of the reference model in order to induce specific mechanism patterns throughout the response. Then, all the systems were subjected to the action of two intrinsically different bidirectional ground motions (El Centro, California, 1941 (***CEN***) and Secretaria de Comunicaciones y Transportes, Mexico City, 1985 (***SCT***)), acting at different angles of incidence. For each angle of incidence, the design base shear coefficient is scaled down, from a starting value associated to elastic behavior, until impending collapse is attained. The base shear coefficient associated to this point is called *dynamic collapse coefficient* (C_C), and it is defined as the minimum required value of the seismic base shear coefficient to prevent structural dynamic instability. From this study, the following conclusions can be made:

For the reference model, C_C and its associated collapse mechanism pattern are dependent on the angle of incidence except for purely rotational mechanisms. The mechanism patterns of the *reference model* correspond to those associated with the minimum values of the maximum monotonic energy dissipation capacity.

It is reasonable to predict the dynamic collapse coefficient C_C for the reference model by obtaining the maximum C_C from all induced mechanism models, which are more likely to be eventually represented by simplified systems. This observation shows the potential to predict the dynamic collapse coefficient and the mechanism that leads to dynamic instability from the study of a set of predefined mechanism patterns, that could be reduced to equivalent single degree of freedom systems.

Kinetic and damping energies are lower-boundered by the corresponding elastic system energies for CEN, but they are upper-boundered by the elastic energies for SCT. However, hysteretic energies for the elastic system are lower bound values of the hysteretic energies associated to near-collapse response for both ground motions.

Total energy does not significantly depend on the orientation or the mechanism pattern for CEN ground motion. However, it is strongly affected by the orientation and the mechanism pattern when the models are subjected to SCT, which is strongly directional, particularly for translational mechanisms.

The total energy demanded from the models is similar to that demanded from the elastic model for the CEN ground motion. However, when the models are subjected to SCT, the total energy demand becomes much higher than in the elastic model, due to the large amount of plastic energy dissipated through the long SCT motion.

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